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Turbulence, Climate and Supercomputers

Abstract
Turbulence is often referred to as the last mystery of classical physics. Although turbulence is ubiquitous and prominent in our daily lives – from the mixing of milk in a cup of coffee to the perpetual motion of the atmosphere and the resulting weather variation – our understanding of this complex phenomenon is comparatively very limited (e.g., Davidson et al., 2011).

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Keywords
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Turbulence, climate and supercomputers

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The turbulent nature of gases and liquids

Turbulence is often referred to as the last mystery of classical physics. Although turbulence is ubiquitous and prominent in our daily lives – from the mixing of milk in a cup of coffee to the perpetual motion of the atmosphere and the resulting weather variation – our understanding of this complex phenomenon is comparatively very limited (e.g., Davidson et al., 2011).

It is difficult to precisely define turbulence. When gases and liquids are subjected to a good stir, chaotic motions emerge that comprise of swirls of various sizes. Turbulence broadly describes this disorderedly motion of fluids. A striking instance of the turbulent nature of the ocean is shown in figure 1a, an image taken by NASA's Aqua satellite and shows the Northern coast of Norway and the surrounding Barents Sea. Although the ocean motion is rarely visible, in this case, a phytoplankton bloom changes the color of water to lighter shades of blue. Thus, the complex and random character of the turbulent ocean becomes distinctly visible.

Scientists and engineers who study and try to predict the behavior of turbulent flows face two main challenges: (*i*) the fluid motions appears irregular and random, and (*ii*) tackling the multitude of scales that are encountered.

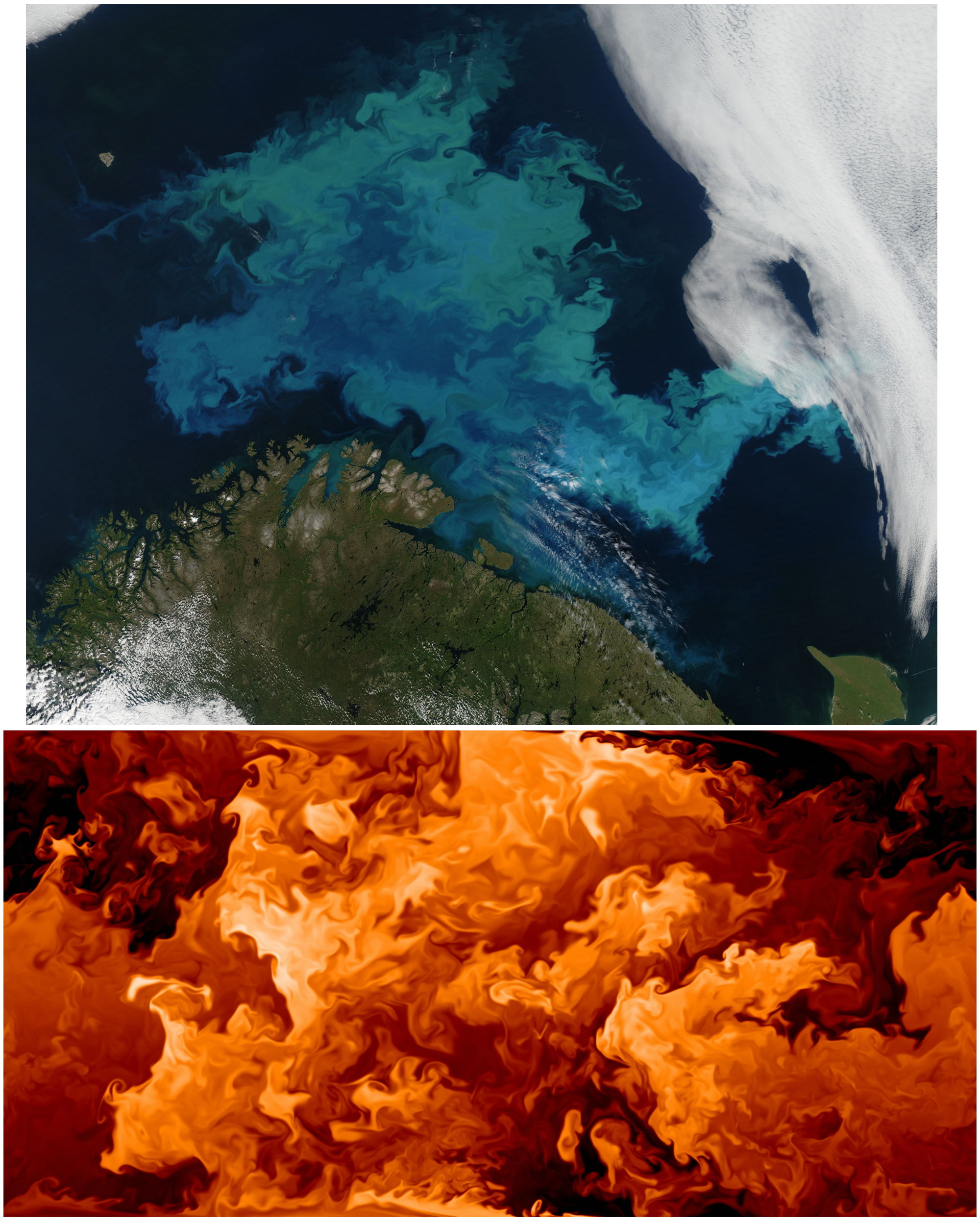

Figure 1 (*a*) Turbulence in the ocean. This image was captured on August 17, 2011, by NASA's Aqua satellite and shows a part of the Barents Sea and the Northern coast of Norway. Light blue colors are phytoplankton. In this case, phytoplankton is acts like a tracer that marks the turbulent motion of the ocean. The area shown is about 300 by 250 miles. (*b*) Simulated turbulence on a supercomputer. Colors correspond to the concentration of a passive scalar, such as small temperature variations, water vapor or carbon dioxide in the atmosphere. The image is a vertical slice taken from a three-dimensional simulation. The simulation is part of a series that investigates the dynamics of atmospheric turbulence with the goal of improving the understanding and prediction of weather and climate. Although panels (*a*) and (*b*) correspond to markedly different instances of turbulent flows, the similarities in their structure are notable.

How do we deal with something that appears random? The atmosphere and ocean are turbulent and irregular but at the same time follow some underlying physical laws. For instance, it is impossible to say with certainty if in two weeks from now it will be cloudy, but we can be very confident that a summer day will be warmer than a winter day. The study of turbulent flows aims to discover the fundamental physical laws, or in other words, to extract the predictable behavior out of events that appear, at first instance, irregular.

Clouds and climate

A visible manifestation of the turbulent atmosphere are clouds, particularly puffy clouds that form near the surface. Clouds are dispersions of drops and ice particles embedded in and interacting with a complex turbulent flow (Bodenschatz et al., 2012). They are very effective at controlling the amount of solar energy that is absorbed by the Earth's atmosphere and surface. For instance, the presence of clouds provides a welcome cooling sensation on a warm summer day. The limitations in our understanding of clouds are prominently manifested in climate prediction simulations where for quite some time now clouds remain the largest source of uncertainty in climate projections (Stephens, 2003; IPCC, 2007; The Economist, 2010). A large part of the difficulty comes from the yet unknown character of atmospheric turbulence.

Supercomputers

There are many ways to study turbulence. A field that is currently growing rapidly is computer simulation, as we can attest by the swift increase of the capabilities of the electronic devices that are part of our daily routine. Scientific computing is an exciting and fast-paced field of science and technology that contributes important advances in our knowledge of turbulent flows. Simulation is intimately linked to prediction. For example, because the modern improvements in computing power and techniques, it is now common practice for car or airplane manufactures to predict and optimize performance and fuel efficiency without having to resort to expensive and time-consuming testing.

Unfortunately, even with the most powerful computers that are anticipated in the foreseeable future, the entire range of sizes of the atmospheric motions cannot be simulated. For instance, simulating the entire range of motions observed in a hurricane requires tracking the state of the atmosphere in tiny boxes with sides of about 1 mm in a region of roughly 500 miles. The amount of computation and the computer memory that is required is prodigious. To circumvent this impediment two alternatives exist.

First, we can simulate only the largest motions and resort to a procedure that represents the effects of the smallest swirls without explicitly computing their evolution. This technique is called ‘turbulence modeling’ and is routinely used by the Weather Service for forecasts. Because of our limited knowledge about the nature of turbulence, ‘turbulence models’ can often be inaccurate, which sometimes results in incorrect long-term weather predictions.

Second, we can resolve the smallest flow motions and leverage computer power in order to capture the largest possible motions. Although the limitations associated with the use a turbulence model are not present, the drawback of this option is that large objects, e.g. a thunderstorm cloud, cannot be simulated because of insufficient computer power. However, present-day computers allow simulations that capture ranges of scales comparable with many engineering applications. Figure 1b shows an image from such a simulation that corresponds to turbulent mixing of a passive substance, such as small temperature variations, water vapor or carbon dioxide in the atmosphere (Chung & Matheou 2012, Matheou & Chung 2012). The simulation was carried out using the Pleiades computer at NASA Ames Research Center in

Mountain View. Powerful computers like Pleiades are aptly called supercomputers. When the simulation of figure 1b was performed, Pleiades was the seventh most powerful computer in the world.

Scientific visualization and art

Scientists and engineers utilize the rigor of mathematics to analyze or communicate ideas and results pertinent to turbulent flows. However, images like the ones of figure 1 are an integral part of the process of discovery. The images are produced by the practice of scientific visualization where data are graphically illustrated in order to glean insight, elucidate, or demonstrate the relevant physics. Considered in this narrow view, the illustrations created from scientific data, do not share a connection with art. However, a viewer will notice that these images have an intrinsic aesthetic value.

Apart from aesthetics, scientific visualization shares two main attributes with artistic expression. First, like art, it is a medium of communication. A scientist cannot alter the data but can use creative ways to present them in order to illustrate specific features, for example, through appropriate choices of viewpoint, color and contrast. An effective image can convey a message efficiently and effortlessly. It is difficult to describe the structure of turbulent flows by referring to coexisting swirls of various sizes. Figure 1 makes this short description much more meaningful. Second, the images of figure 1 allow us to perceive and grasp events that are difficult to discern and recognize. Often our immediate perspective is limited. For instance, we cannot comprehend the detailed structure of the ocean in figure 1a merely by cruising the Barents Sea, whereas the satellite image puts the variations of the seawater color into a broader perspective. Figure 1b illustrates small temperature variations, a quantity that is not visible to the human eye. Similarly, art aims to convey the broader perspective of events, elucidate aspects that are not evident, and draw attention to fine contrasts and sensitivities.

Although art and science are distinct disciplines, they often intersect. The illustration of fluid flows and turbulence in particular is one of the strongest manifestations of the synergy between art and science.

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